Channel

Background and Objectives

Stream channels are shaped by a number of important factors that interact to create characteristics unique to each stream. Some factors, such as the climate, geology, stream gradient, and drainage area of a stream, are typically unchanged by human activities. Other factors, however, such as the supply and transport of sediment, the character of riparian vegetation, and the volume and timing of water runoff can be influenced by land-use activities. These factors all influence the channel morphology and dictate the quality and quantity of habitat available for aquatic-dependent species. Studying channel morphology can thus provide a measure of changes in habitat conditions and together with the Aquatic Life module can help to assess the health of the aquatic system.

Evaluating the effect of land-use activities on channel conditions can be difficult because stream channels are affected by the interaction of many watershed processes that often have a great deal of natural variability. Large-scale projects such as dams or levees may create easily observed impacts on flood discharge and floodplain characteristics but may also have more subtle long-term impacts on important factors such as sediment storage, channel bed elevation, and nutrient transport. A great deal of field data collection and analysis may be necessary to provide evidence that land management impacts, and not natural disturbances such as floods, are responsible for a change in channel conditions. The Channel analyst will need to work closely with other analysts, particularly from the Erosion, Vegetation, Aquatic Life, and Water Quality modules, to conduct a comprehensive assessment.

The objectives for a Level 1 assessment are to characterize the types of channels that occur within the watershed and to identify where changes in channel morphology are most prevalent. The Level 1 assessment relies primarily on the analysis of topography, geology, and soil maps together with a historical set of aerial photographs. Some fieldwork is encouraged to verify channel characteristics observed on maps and photographs. Information on channel types within the watershed can be used to develop hypotheses about the cause of observed channel changes and potential future effects. Further evaluation and data will be necessary to provide evidence for any cause-and-effect relationships.

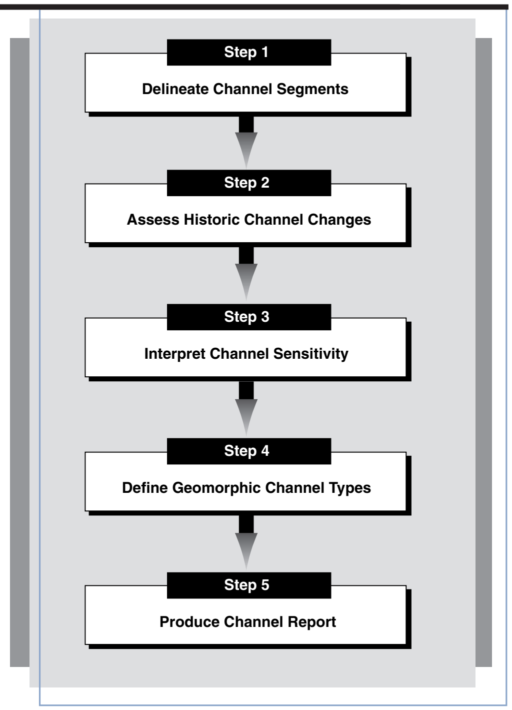
Level 2 methods and tools require specialized expertise and experience in evaluating channel behavior, conducting field surveys, and interpreting channel-related data. A Level 2 assessment may be necessary when multiple land uses are impacting the channel or when a defensible, quantitative analysis is required. Potential field methods include cross-sectional surveys to evaluate channel width/depth ratios, bankfull flows, hydraulic roughness, and substrate characteristics. More advanced and long-term evaluations may also involve measurement of discharge, bedload transport, and fine sediment transport. Analysis techniques can include sediment budgets, stream power calculations, and use of sediment transport equations and models.

Channel Module Reference Table

Critical Questions	Information Requirements	Level 1 Methods/Tools	Level 2 Methods/Tools
C1: How does the physical setting of the watershed influence channel morphology?	• Air photos • Topography maps • Geology maps	• Anecdotal information • Observations from maps and air photos • Existing channel classification • Existing survey data • General channel typing	• Field surveys • Channel classification • Geomorphic channel typing
C2: How does climate and the frequency, magnitude, duration, and timing of floods affect channel conditions?	• Annual peak flow data • Climate data • Historical set of air photos	• Anecdotal information • Air photo observations • General channel typing	• Field surveys • Channel classification • Geomorphic channel typing • Flood analysis (Hydrology)
C3: How and where has the behavior of the channel changed over time?	• Historical set of air photos	• Anecdotal information • Air photo observations	• Field surveys • Channel classification • Geomorphic channel typing
C4: How and where have changes in sediment inputs (erosion) over time affected channel conditions?	• Historical set of air photos • Sediment source data	• Anecdotal information • Air photo observations	• Field surveys • Sediment budget • Soil Creep Estimation
C5: How and where have changes in riparian vegetation influenced channel conditions?	• Historical set of air photos • Riparian vegetation data	• Anecdotal information • Air photo observations	• Field surveys
C6: How and where have changes in stream discharge influenced channel conditions?	• Streamflow data • Historical set of air photos • Water withdrawal data	• Anecdotal information • Air photo observations • Hydrology data	• Streamflow models (Hydrology) • Bank erosion analysis (Erosion)
C7: What are the sediment transport characteristics of streams in the watershed?	• Sediment transport data • Streamflow data		• Suspended or bedload transport data • Sediment transport equations • Sediment budget (Erosion)
C8: Where does sediment storage occur in the channel and on the floodplain, and how much sediment is stored?	• Aerial photographs		• Field surveys • Aerial photograph analysis • Sediment budget (Erosion)
C9: How and where has the dredging, straightening or shifting of streams affected channel behavior?	• Historical set of air photos	• Anecdotal information • Air photo observations	• Field surveys • Sediment budget (Erosion)
C10: How does the presence and management of dams and levees affect channel conditions?	• Streamflow data • Historical set of air photos	• Anecdotal information • Air photo observations	• Reservoir models • Sediment transport models
C11: What is the potential for change in channel conditions based on geomorphic characteristics?	• Air photos • Topography maps • Geology maps	• Observations from maps and air photos • Existing channel classification • General channel typing	• Channel classification • Geomorphic channel typing • Field surveys

Level 1 Assessment

Step Chart



Data Requirements

- Topographic maps (1:24,000 scale [7.5-minute series] or finer preferred).
- Aerial photographs (1:12,000 scale preferred). Photographs recording major storm events and changes in land use activities are particularly useful for assessing changes in channel conditions.
- Geomorphic maps (if available).
- Landform map and erosion data (coordinate with Erosion module, if applicable).
- Land use map (as necessary).
- Climate and streamflow information (coordinate with Hydrology module).
- Information on water use/extraction and dam management (coordinate with Hydrology module).

Products

- Form C1. Historical channel changes
- Form C2. Geomorphic channel type characteristics
- Map C1. Channel segments
- Map C2. Geomorphic channel types
- Channel report

Procedure

Step 1. Delineate channel segments

Dividing the stream network into segments provides an initial interpretation of channel character that integrates the landform (i.e., geology, soils, and topography) and fluvial features of the valley with channel relief, pattern, shape, and dimension. A channel segment defines a portion of the stream network with relatively uniform channel features.

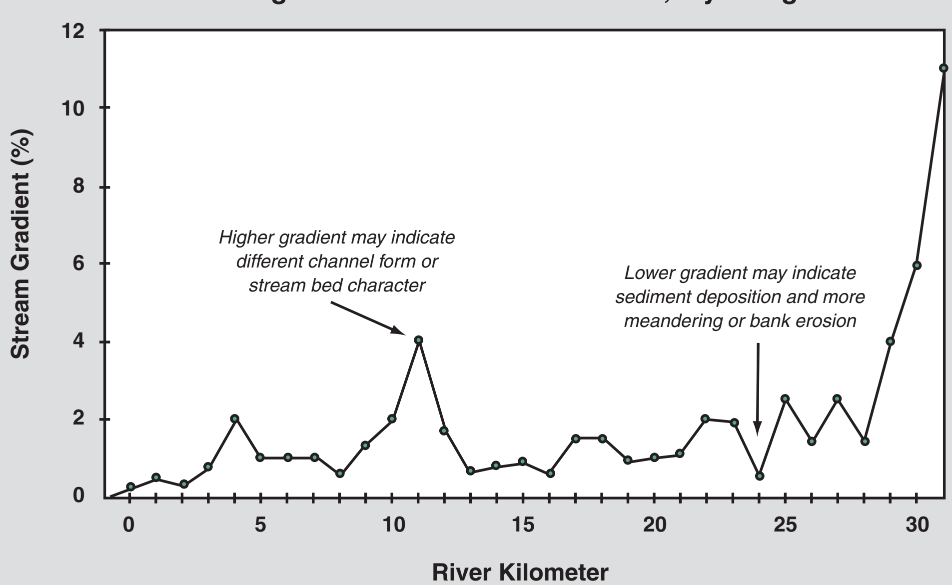
Using aerial photographs, topographic maps, and geology or soil maps, divide the stream network into segments by identifying locations where the channel characteristics change. Channel segments provide a preliminary classification system and serve as a reference for cataloging data and other observations. Characteristics that can be used to delineate segments include the following:

- Fault locations, major geologic structures, or changes in surface rock types.
- Inflow of major tributaries.
- Engineering structures, such as dams, diversions, levees, or single conveyance channels.
- Local variation in channel pattern.
- Channel confinement.
- Channel gradient (Box 1).

Box 1. Creating a Longitudinal Stream Profile

A relatively simple analysis of stream gradient can provide useful information for channel classification and highlight stream reaches that may require further study. Using a topographic map, determine the stream gradient at regular intervals for the entire length of the stream. Stream gradient is defined as the change in elevation divided by the length of the stream reach. Most streams have a generally increasing trend in slope as measured from the mouth of the stream to its headwaters. Abrupt increases in slope typically signify areas of higher stream energy and may indicate a change in confinement, geology, or sediment transport characteristics. Abrupt decreases in slope typically signify areas of lower stream energy and often correspond to areas of increased sediment deposition, broader floodplains, and greater stream meandering.

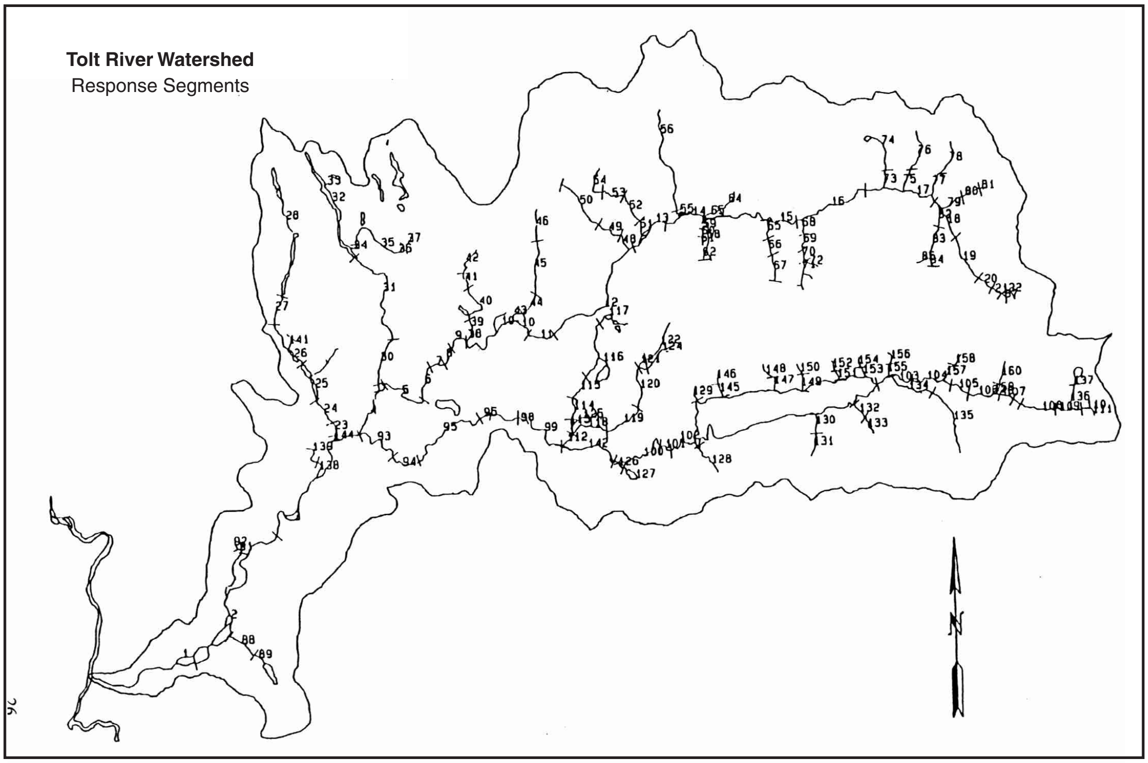
Longitudinal Profile for Bear Creek, Wyoming



- Changes in riparian vegetation.
- The presence, size, or shape of floodplains, terraces, fans, or sand/gravel bars.

Delineate channel segments on a topographic map to create Map C1 (Figure 1). In large watersheds with numerous tributaries, it may be useful to assign a numeric code to the mainstem channel and an alphanumeric code (e.g., A1) to each tributary system.

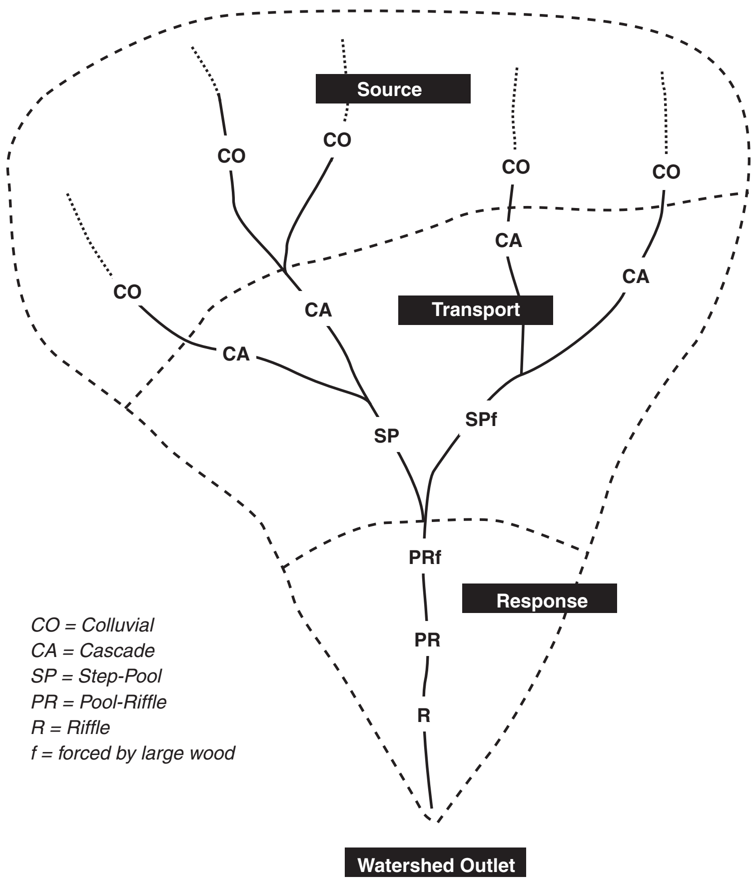
Figure 1. Sample Map C1



The length and number of channel segments will depend upon the watershed size and the goals of the Watershed Assessment. The analyst should not commit too much time to examining minor differences in channel character because more data will be collected to refine the channel classification.

Existing channel classification systems can also be used to delineate channel segments. Numerous classification systems exist that use one or more parameters to divide the channel network (Figures 2 and 3) (Graf and Randall 1997; Montgomery and Buffington 1993; Rosgen 1994; WFPB 1997). In most cases, the analyst will want to use the classification system that is most widely applied in the region. The

Figure 2. Watershed map illustrating application of stream classification based on stream gradient and morphology (Montgomery and Buffington 1993)



analyst should, however, evaluate the utility of using available classification systems to meet the WAM project goals. Considerations may include scale of investigation, available data, and the need for field data.

Step 2. Assess historical channel changes

A wide variety of historical data are useful for reconstructing past channel changes. In most cases, aerial photographs will provide the primary source of historical data. Photographic coverage that spans decades and records major events (e.g., floods, catastrophic events) is necessary to determine trends in channel conditions through time. The historical analysis is also the first step in developing hypotheses about channel response to management activities.

Historical changes and trends in channel attributes provide an important context within which to assess current and potential channel conditions. Aerial photograph analysis is an efficient method for focusing field efforts, as well as a valuable resource for indicating historical channel change and response.

Changes in channel morphology may involve the following elements:

- Engineering structures (diversions, levees, etc.).
- Channel pattern (e.g., sinuosity, braiding).
- Channel width.
- Size and form of sand/gravel bars.
- Extent and frequency of bank erosion.

Figure 3a. Stream types: gradient, cross section, plan view (Rosgen 1994)

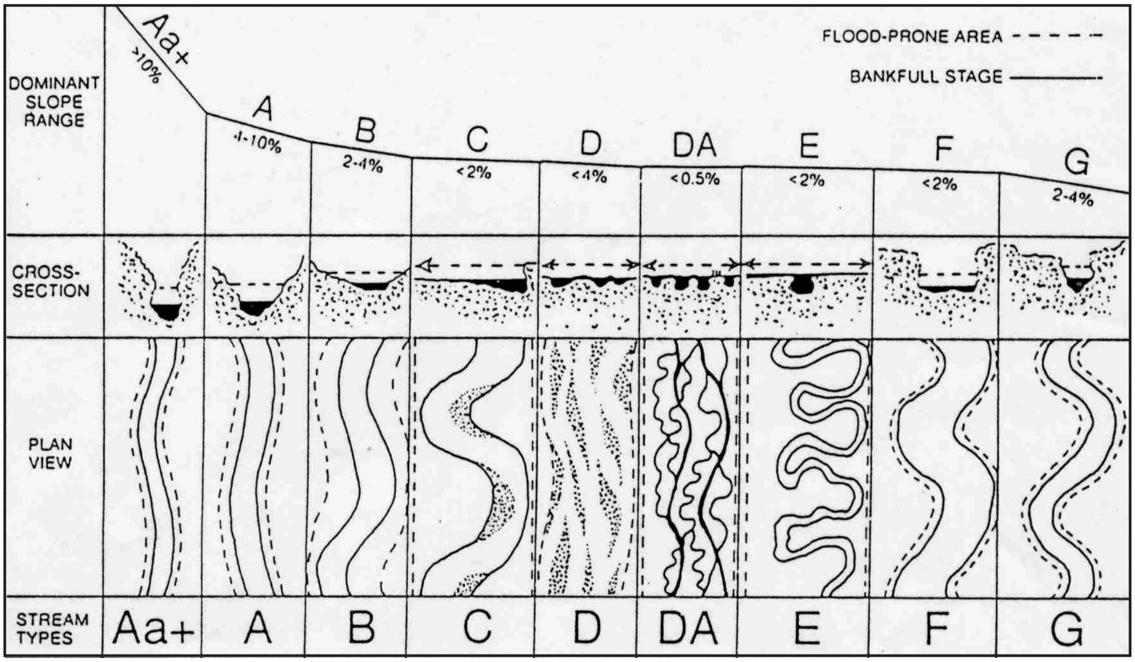
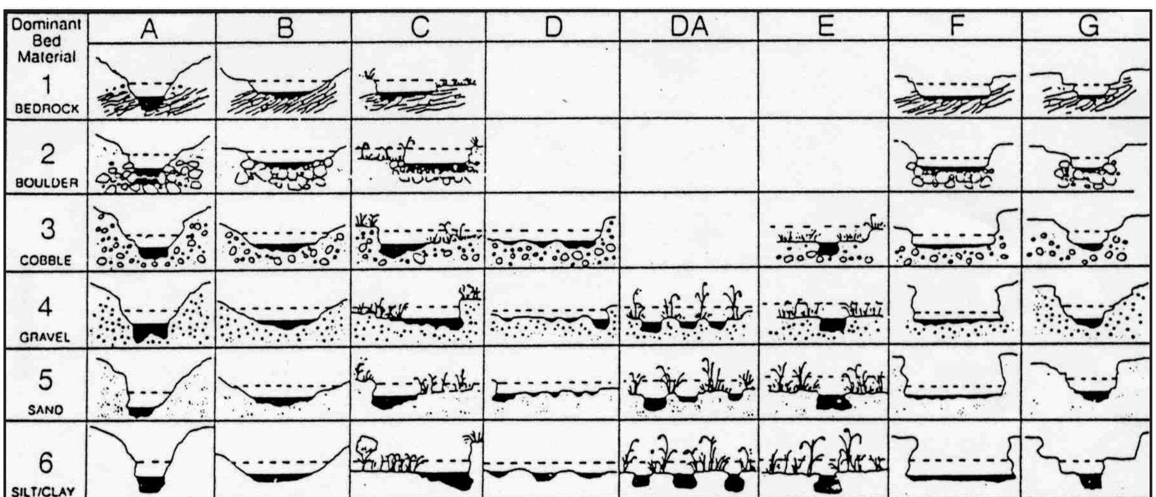


Figure 3b. Cross-sectional view of stream types (Rosgen 1994)



	A	B	C	D	DA	E	F	G
ENTRH.	<1.4	1.4-2.2	>2.2	N/A	>2.2	>2.2	<1.4	<1.4
SIN.	<1.2	>1.2	>1.4	<1.1	1.1-1.6	>1.5	>1.4	>1.2
W/D	<12	>12	>12	>40	<40	<12	<12	<12
SLOPE	.04-.099	.02-.039	<.02	<.04	<.005	<.02	<.02	.02-.039

- Areal extent and stability of floodplains, terraces, and fans.
- Scour from floods or channelized landslides.
- Wood debris loading.
- Canopy opening or changes in vegetation patterns.
- Sediment processes (local storage or erosion).
- Road crossings.

Reference points (i.e., fixed landmarks) should be identified so changes in channel dimensions and forms can be measured in successive aerial photographs. Measuring the same cross-sectional area (transect) allows the Channel analyst to compare changes in channel width and area over time. Measurements from different sets of aerial photographs will need to be corrected to account for scale differences and distortion. For small channels, direct observation of channel width may not be possible due to dense riparian vegetation. For these channels, canopy opening provides a useful surrogate for channel width (Grant 1988). In larger channels, changes in gravel bar size and vegetation cover may also be observed over time. To correlate channel changes with floods, coordinate with the Hydrology analyst. Where historical changes are observed, record observation on Form C1 (Figure 4).

Hydrology ▶

Figure 4. Sample Form C1. Historical channel changes

Channel segment(s)	Historical changes	Other observations
1	Channelized with concrete banks since 1903	Radical changes have virtually eliminated aquatic habitat. Concrete channel minimizes influence of sediment, water, and vegetation.
2, 6	Levees since pre-1900	Dirt levees minimize sediment deposition. Flood scour compromises levee integrity.
3, 7, 11, 12, 13	Possible increased entrenchment	Interviews and aerial photos indicate channel incision over past 50 years, possibly due to removal of in-stream wood debris and increased runoff from urbanization.
4, 5, 9, 10	Increased sediment deposition and bank erosion	Low-gradient section with natural tendency for sediment storage and channel migration. Erosion from agricultural lands, grazing, and vegetation removal has probably increased sediment supply.

Step 3: Interpret channel responsiveness

Understanding the factors that control and influence channel processes is critical to the Synthesis step of the WAM process. The potential response of each channel segment to changes in sediment, water runoff, and vegetation will need to be evaluated in the context of historical channel behavior and the natural geomorphic setting (e.g., geology, gradient, valley confinement). Table 1 lists possible channel responses. The exact nature and duration of the responses will vary depending on the watershed and channel characteristics and the causes for the changes.

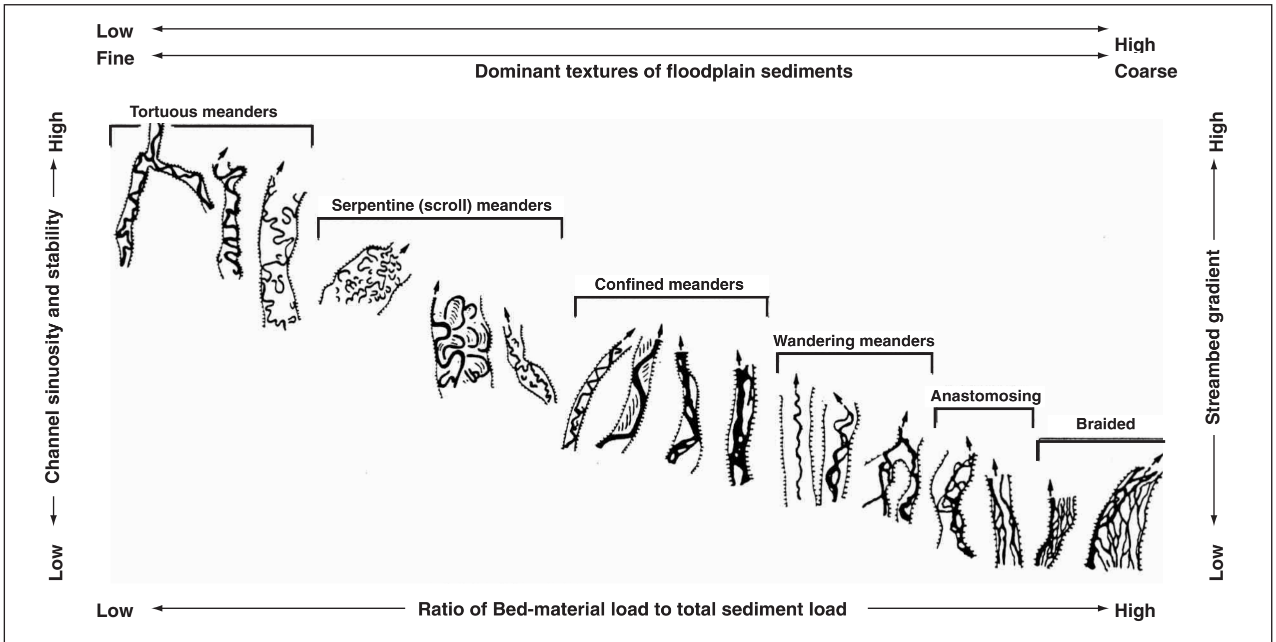
Considering evidence from aerial photographs, stream surveys, watershed reports, anecdotal information, and observations, identify channel segments that have shown a significant response to floods, vegetation disturbance, or changes in sediment supply (Figure 5). A change in channel behavior from natural or human disturbances generally signifies the potential for future changes at these channel segments. Consult with the Hydrology, Erosion, and Vegetation analysts to help correlate channel changes with large floods, periods of increased erosion, or substantial changes to upland or riparian vegetation. The analysts can provide useful information on the magnitude, frequency, distribution, and timing of changes in these watershed processes. The Historical Conditions and Community Resource analysts may also have useful information on past conditions or historical practices in and around the channel. Hypothesized connections between historical practices and changes in channel conditions will often require further Level 2 assessment to provide evidence for causal links.

Table 1. Examples of potential channel responses to changes in water runoff, sediment supply, or vegetation

Change	Potential Channel Responses
Increasing water runoff	• Entrenchment (incision) • Gully formation • Coarsening of stream bed (i.e., less fine sediment) • Increased bank erosion
Decreasing water runoff	• Aggradation • Increased fine sediment in the stream bed • Decrease in channel width
Increasing sediment supply	• Aggradation • Larger, more frequent sand and gravel bars • Increased fine sediment in the stream bed • Increased channel movement • Increased flooding
Removal of upland vegetation	• Increased flooding • Increased sediment delivery
Removal of riparian vegetation	• Increased bank erosion • Aggradation • Fining of the stream bed • Increased channel movement • Channel widening

Hydrology
Erosion
Vegetation
Historical Conditions
Community Resources

Figure 5. Examples of channel form as a function of gradient, particle size, and sediment supply



Adapted from Selby (1985)

In addition to considering external agents for channel changes, it will be important to consider the geomorphic setting of the channel to help evaluate where a high potential for change exists naturally. A longitudinal stream profile will often help to identify segments where a shift in gradient will increase the potential responsiveness of the channel. Evaluate whether changes in geology or soil type correlate with a change in channel pattern or behavior. Finally, examine the correlation between segments with a natural potential for responsiveness and evidence of historical changes in channel behavior. These correlations can be used to identify other channel segments with a high potential for responsiveness, even if these segments have not changed significantly in recent times.

Information on changes in channel behavior will be used in the following step to help define geomorphic channel types and to rate the responsiveness of channel types to changes in sediment, water runoff, vegetation, and other disturbances.

Step 4. Define geomorphic channel types

Defining geomorphic channel types relies on the work conducted in the previous steps, as well as products from other modules. Geomorphic channel types are groups of segments that have similar characteristics and that are expected to respond similarly to changes in water runoff, sediment, and vegetation. Channel typing can be useful to help integrate information on hillslope processes with information on channel conditions to ultimately assess aquatic habitat sensitivities.

Erosion
Hydrology
Vegetation

Specific criteria for developing channel types do not exist, so the Channel analyst must use available data and professional judgment to define appropriate categories. Channel types should consider both stream and valley form to characterize segments with similar geomorphic responsiveness. Group segments with similar channel conditions and potential responses to altered water runoff, sediment supply, or vegetation or to natural disturbances (e.g., floods, hurricanes, fire). Existing channel classification schemes (Graf and Randall 1997; Montgomery and Buffington 1993; Rosgen 1994; WFPB 1997) often consider many of these factors. A geomorphic channel type will typically consist of a group of channel segments, but a unique segment may warrant its own channel type. It may be helpful to consult with the Erosion analyst for a further understanding of the land types present in the watershed. Although the channel types are likely to be related to geomorphic land types, their delineation may not directly coincide.

Erosion

Creating geomorphic channel types provides a way of organizing information from the Channel module and other modules to describe linkages between hillslope processes and aquatic resources. Identification of channel types may involve some generalization such that some local reaches may not have the same response potentials as other reaches of the same type (WFPB 1997). Prior to the start of Synthesis, the Channel analyst should work with the other module analysts to interpret potential linkages between land use practices, changes in watershed processes, and channel responses.

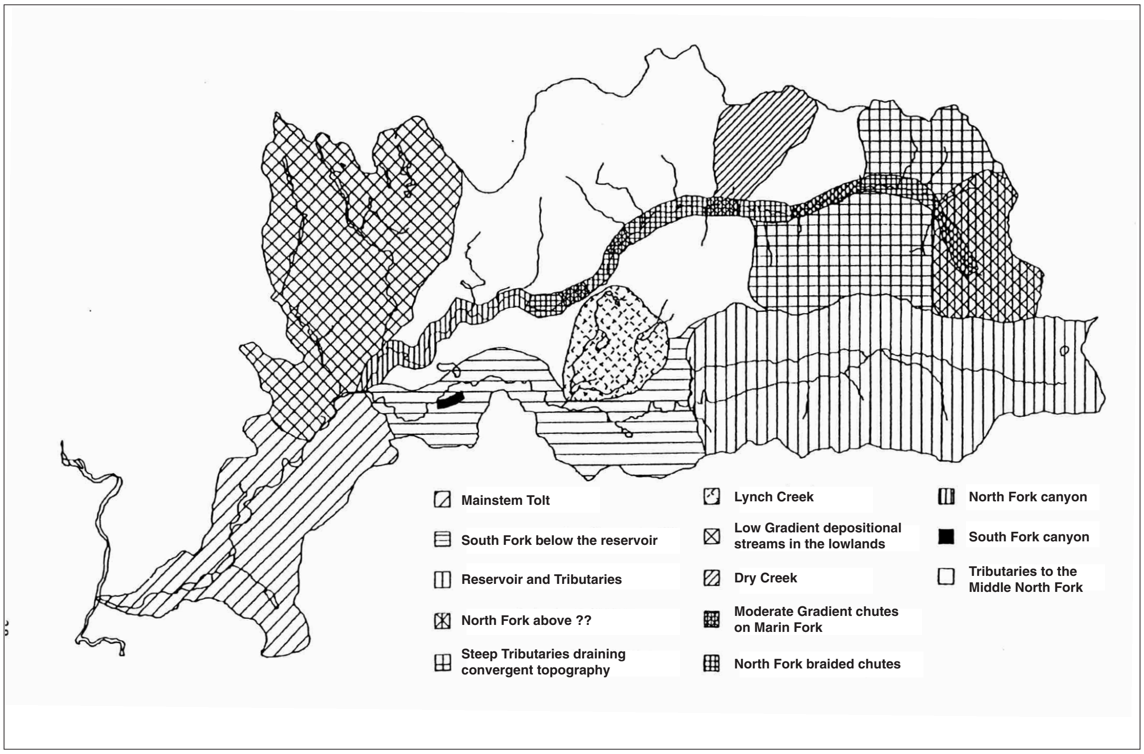
Erosion
Hydrology
Vegetation
Aquatic Life

Identify geomorphic channel types on Map C2 (Figure 6). Form C2 can be used to describe each channel type and summarize the hypothesized responsiveness of each channel type (Figure 7). Responsiveness for each channel type should be rated "High," "Moderate," or "Low" relative to changes expected in other channel types. Since the response potential of each channel type is based primarily on remote analysis of maps and other data, ratings should be considered preliminary. Field verification and further analysis will often be necessary to provide support for responsiveness ratings.

Step 5. Produce Channel report

The analyst should produce a report that organizes and presents the methods, data, and results of the Channel assessment. The report should include a brief narrative along with

Figure 6. Tolt watershed geomorphic channel types (adapted from Washington Forest Practices Board 1997)



tables, graphs, forms, and maps to provide the scientific justification for channel typing and responsiveness ratings. The type of data or information necessary for a high confidence level in the analyses and interpretations will not always be available; therefore, the analyst must address the confidence level of the data and work products. The degree of confidence that can be assigned to the products depends upon a number of factors:

- The amount, type, and quality of available information.
- The relative confidence for each work product.
- The extent of field work.
- The experience of the analyst.
- The complexity of the geology and terrain.
- Aerial photograph and map quality.
- Multiple lines of evidence for inferred changes.

Figure 7. Sample Form C2. Geomorphic channel type characteristics

Channel type	Description	Channel segments	Potential responsiveness rating			Evidence supporting rating
			Sediment	Runoff	Vegetation	
Lower Confined Mainstem	Low gradient (<1%), broad historic flood-plain, islands, river confined by levees	1 and 2	Moderate	High	Moderate	• Floods in 1980s undermined levees • Rip-rap instead of trees maintain river banks • Wetlands historically provided floodwater storage
Entrenched Mainstem	Low gradient (<1%), recent channel entrenchment	3	Low	Moderate	Low	• Historical floodplain not inundated during floods • Substantial bank erosion, but no change in pattern following floods in 1980s
Tributaries on River Floodplain	Low gradient (<2%), small meandering and braided streams, wetlands, and old oxbows common	A1, B1, and C1	High	Low	High	• Increased sediment supply could cause sub-surface flow • Root system from riparian trees maintain streambanks • Runoff spreads across floodplain
Tributaries in Naches Formation	2-4% gradient, entrenched, with high, raw banks in weak sandstone	A2, A3, C2, and D1	Low	High	High	• Floods cause severe bank erosion • Wood debris important for storing sediment
Meandering Upper Mainstem	2-6% gradient, gravel and cobble substrate, numerous rapids	4 - 8	Moderate	Low	Moderate	• Sediment not a problem, but more fine particles could change sub-strate character • Trees important for shade and bank stability

Level 2 Assessment

Stream channels are formed by a complex set of physical processes. Interpretations of channel conditions can be difficult because of the dynamic interactions among climate, water flow, and sediment transport. Determining natural or historical conditions is often a challenge because many streams have been significantly modified by human activities. Understanding the natural disturbance history can also be important for understanding current conditions. Evidence of channel disturbance from floods, landslides, or fires is often observable in channel and floodplain deposits for many decades following the disturbance.

Because of the complexity of channel processes, parameters used to assess stream conditions should be established in the scientific literature so that observations can be credibly supported. Parameters should focus on geomorphic forces that can be quantified (e.g., channel gradient, substrate size, shear stress) so that the analysis is repeatable and changes can be reliably measured. Ideally, parameters will be applicable to a wide range of channel types and account for variability from reach to reach. While some channel variables require long-term monitoring data, many useful parameters are relatively easy and inexpensive to measure in the field or from remote sensing.

The Level 2 assessment is divided into three general approaches to channel investigation:

1. Stream channel surveys.
2. Detailed channel classification.
3. Sediment budgets.

The following sections do not provide detailed instructions but offer general guidelines and references to other sources that elaborate on these procedures. The following books provide general information about channel processes and ways to evaluate them:

- *Rivers: Form and Process in Alluvial Channels* (Richards 1982).
- *Water in Environmental Planning* (Dunne and Leopold 1977).
- *The Fluvial System* (Schumm 1977).
- *Drainage Basin Form and Process* (Gregory and Walling 1973).
- *Fluvial Processes in Geomorphology* (Leopold et al. 1964).

Stream Channel Surveys

Field surveys are a critical element of any analysis of stream channel conditions. Fieldwork provides quantitative data on stream conditions that ideally can be extrapolated to evaluate conditions at a watershed scale. Field surveys can help with the following:

- Characterizing variation in channel features.
- Evaluating channel types.
- Applying or verifying channel classification schemes.
- Clarifying observations from maps and aerial photographs.
- Establishing reference sites to monitor changes in channel condition.

The number and location of surveys will vary depending on the objectives of the assessment and available time and resources. Where measurements are to be used for flow or sediment transport calculations, sites should be straight, single-stranded, and unobstructed to minimize complications. Where measurements will be used to compare conditions between streams, it will be important that characteristics such as gradient, substrate, and channel form are similar so that the effects of land management can be better isolated. Measurements for baseline and trend monitoring should be located in areas where change is likely and will be visible. In general, locally dynamic sites such as tributary confluences or alluvial fans should be avoided.

The following sections provide a brief description of techniques for examining channel variables. Detailed instructions on conducting stream surveys can be found in the following sources:

- *Stream Channel Reference Sites: An Illustrated Guide to Field Technique* (Harrelson et al. 1994).
- *Survey Methods for Ecosystem Management* (Myers and Shelton 1980).
- *Timber-Fish-Wildlife (TFW) Monitoring Program Method Manual for the Reference Point Survey* (Pleus and Schuett-Hames 1998).

Longitudinal and cross-sectional stream surveys

A stream reach can be characterized using a combination of longitudinal and cross-sectional surveys. The surveys should include a plan-view sketch of the stream reach and detailed notes on channel characteristics to help identify important benchmarks and measurement points. A surveyor's level and rod along with fiberglass tape can be used to map the location and elevation of important channel features. Channel features can include the stream gradient, bankfull width, bankfull depth, and floodplain features. Data on stream substrate, sediment particle size, and hydraulic roughness can also be collected at cross-sectional survey points (Box 2). The following paragraphs provide more information on measuring specific channel features.

Box 2. XSPRO for cross-sectional data

XSPRO is a USFS computer program designed for use by specialists and non-specialists alike to calculate hydraulic parameters based on cross-sectional surveys (Grant et al. 1992). The program accepts x- and y-coordinates from the cross-sectional survey along with depth of flow (either observed or inferred) and calculates a series of hydraulic parameters, including shear stress and stream power. The program produces both graphical and tabular outputs. XSPRO is available free of charge and is relatively easy to use. It is available from West Consultants at **http://www.westconsultants.com.**

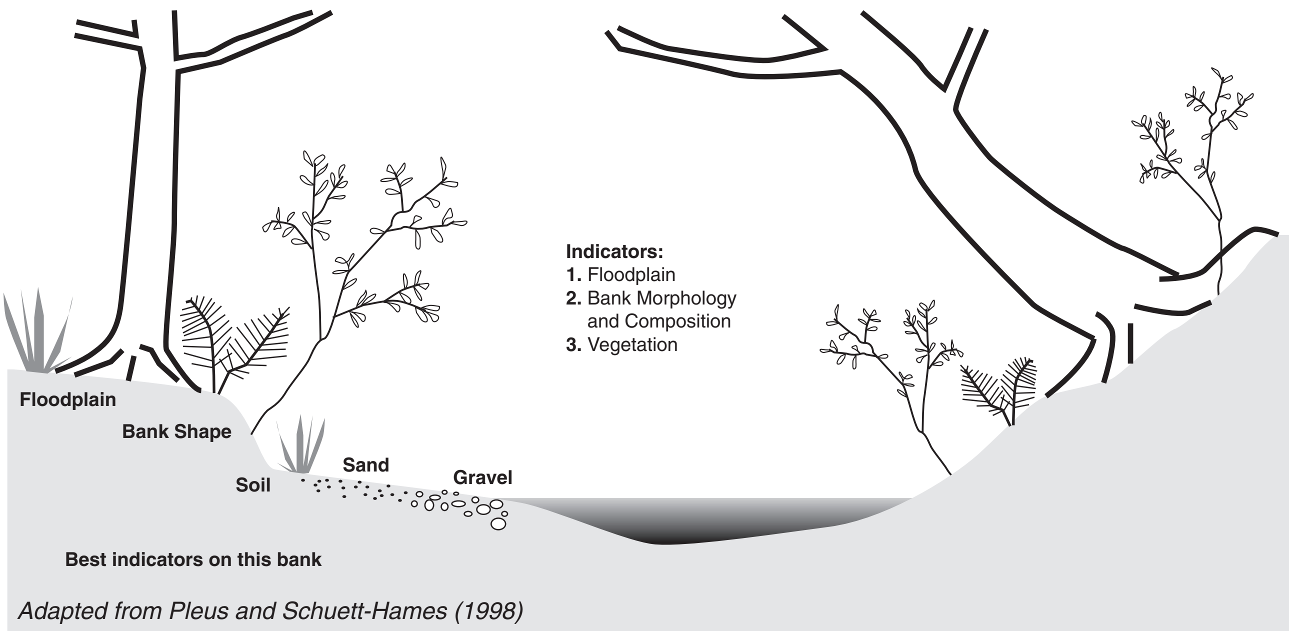
Channel width and depth

The most useful measure of channel width and depth is at bankfull flow because this discharge is morphologically definable in the field and typically has the greatest control on the dimensions of alluvial channels over time (Leopold et al. 1964). Bankfull flow is generally reached once every two years (Dunne and Leopold 1977). Bankfull width and depth refer to the width and average depth of the channel at bankfull flow. While the boundaries of the bankfull channel can be difficult to consistently identify, the edge of the bankfull channel usually corresponds to the start of the floodplain (Figure 8). The floodplain is defined as the generally flat landscape feature adjacent to most channels that is overflowed at times of high discharge (Dunne and Leopold 1977). The start of the floodplain is often characterized by the following features:

- A berm or other break in slope from the channel bank to a flat valley bottom, terrace, or bench.
- A change in vegetation from bare surfaces or annual water-tolerant species to perennial upland or water-tolerant shrubs and trees.
- A change in the size distribution of surface sediments (e.g., gravel to fine sand).

Bankfull width and depth data are necessary for analysis of channel characteristics including the cross-sectional area, width to depth ratio, bed shear, and stream power. Benson and Dalrymple (1967) describe measurement methods in more detail.

Figure 8. Indicators for determining bankfull width



Hydraulic roughness

Hydraulic roughness is a critical part of basic hydraulic calculations because it addresses a loss of energy from turbulence. Less energy to move water and sediment has important implications for water discharge, sediment transport, and erosion rates. The elements of roughness, including particle size, form roughness (e.g., dunes and riffles), and vegetation roughness, can change under natural circumstances or by human intervention. Roughness due to vegetation may also change seasonally.

Manning's n is the most commonly used roughness parameter and is derived from Manning's Equation to calculate stream flow velocity:

$$V = (1/n)(R^{2/3})(S^{1/2})$$

Where: V = velocity (ms^{-1}), n = hydraulic roughness (dimensionless), R = hydraulic radius of the channel (the area of the channel divided by the length of the wetted perimeter) (m), and S = channel slope or gradient.

Manning's n cannot be directly measured but can be estimated if the other variables in the flow equation are known. Estimates of Manning's n have been developed for a broad range of natural and artificial channels. Tabulated values or photographs of representative stream reaches of known roughness can provide useful estimates of hydraulic roughness (Cowan 1956; Chow 1959; Barnes 1967). Estimates of hydraulic roughness on floodplains (Arcement and Schneider 1989) and in dryland streams (Aldridge and Garrett 1973) are also available to provide examples from different regions. Limerinos (1970) provides guidance on calculating roughness from field surveys of the channel bed.

Channel gradient

The gradient of the channel has a direct influence on the velocity of flow and the ability to entrain and carry sediment. The general channel gradient can be estimated from topographic maps, but local gradient changes will not be detected by this approach. Accurately measuring the gradient of the water surface (typically based on estimated bankfull elevation) with a level or transit is important for site-specific evaluations of stream discharge and sediment transport.

Substrate size and distribution

Determining the size and distribution of streambed substrate can provide information on roughness elements and aquatic habitat types. Streambed particle sizes can also be important for evaluating channel stability following disturbances (e.g., regulated dam releases or construction projects on the floodplain).

Classification of substrate type is an easy qualitative descriptor of the channel bed. Categories of substrate size typically include clay, silt, sand, gravel, cobble, and boulder (Table 2). Finer gradations of each particle size such as coarse, medium, or fine may be useful to provide greater detail on the substrate character.

Table 2. Substrate size categories

Substrate	Size Range (mm)
Clay	<0.0039
Silt	0.0039-0.0625
Sand	0.0625-2.0
Gravel	2.0-64.0
Cobble	64.0-256.0
Boulder	256.0-4096.0

Two quantitative methods for characterizing streambed particle size are sieve analysis and the relatively easy Wolman's method of pebble counts (Wolman 1954; Potyandy and Hardy 1994). For either method, a sample of particles is measured at cross-sections of the channel bed or bar. A sieve analysis simply involves filtering a sediment sample through various sieves to characterize the range of particle sizes. The Wolman pebble count relies on measurements from a sample of surface sediments. To create a representative sample, the median diameter of each particle touched by the toe of one foot is measured at every step or series of steps in several passes across the channel. A sample size of at least 100 particles is usually necessary to conduct simple statistical analyses. Reid and Dunne (1996) provide a more detailed discussion of the location and number of samples necessary to characterize substrate. With either method, a frequency distribution is usually created to identify the mean or median diameter (D_{50}) and the diameter at two standard deviations from the mean (D_{16} and D_{84}). Several cross-sections should be evaluated in a reach to determine the general character of the streambed. Harrelson et al. (1994) provides a good description of how to characterize bed and bank materials.

Quantitative analysis of cross-section data

Width to depth ratios

Monitoring changes in channel dimensions can be a useful method for identifying and evaluating trends in channel conditions. One of the simplest comparisons is a width to depth ratio. The depth can be either the average or maximum bankfull depth. Changes in the ratio over time or space are usually indicative of differences in water discharge or sediment transport capacity. Care must be taken to differentiate changes due to episodic events such as flooding from long-term watershed changes such as increased water or sediment supply from urbanization.

Water velocity and discharge

Calculating discharge is a function of the channel area and the velocity of the water. Stream discharge data can usually be obtained from the Hydrology module, although more site-specific estimates may be necessary for stream power and sediment transport analysis.

Hydrology

Locally developed empirical equations are a common tool for estimating discharge. Equations to estimate flood flows have been developed throughout the United States and are relatively easy to apply. Most equations are based on a regression analysis of existing discharge data and are generally a function of the basin area, precipitation, and vegetative cover. The length of streamflow records and the uniformity of the landscape are important to consider in evaluating the accuracy of these predictions.

More accurate site-specific discharge measurements can also be obtained from cross-sectional survey measurements. A number of software packages, such as XSPRO (Box 2), can be used to help estimate discharge using Manning's or other equations. More intensive field methods for calculating discharge generally fall into four categories:

- Volumetric measurement (generally appropriate only for small streams).
- Measurement of stream velocity and cross-sectional area.
- Dilution gauging using a salt or dye.
- Artificial controls such as weirs, with known stage-discharge relationships.

Further information on techniques for measuring velocity and stream discharge can be found in Corbett (1962) and Herschy (1985).

Stream power

Stream power is a measure of the stream's capacity to move sediment over time. Stream power can be used to evaluate the longitudinal profile, channel pattern, bed form development, and sediment transport of streams. It may be measured for an entire stream length or stream reach or per unit of channel bed area. The general form of the stream power equation is as follows:

$$\Omega = \rho g Q s$$

Where: Ω = stream power, ρ = density of water; g = gravitational acceleration; Q = water discharge; and s = slope.

A general evaluation of power for an entire stream or a particular reach can be calculated using the average discharge and average valley or channel slope for the given length. Measurements of stream power per unit of bed area provide a more accurate assessment of the stream's ability to move material because frictional losses of energy are accounted for in the equation.

In addition to measurements of discharge and channel slope at a cross-section, a measure of shear stress (τ) needs to be calculated. Shear stress may be described as the drag exerted by the flowing water on bed sediments and the channel perimeter. Shear stress is defined as follows:

$$\tau = \rho g R s$$

The actual amount of work accomplished by the stream per unit of bed area depends upon the available power divided by the resistance offered by the channel sediment, forms, and vegetation. The stream power equation can thus be rewritten as follows:

$$\omega = \rho gRsv = \tau v$$

Where: ω = stream power per unit of bed area and v = average water velocity.

Consult the reference books on channels listed at the beginning of the "Level 2 Assessment" section for further details on calculating stream power and shear stress.

Detailed Channel Classification

As discussed briefly in the Level 1 assessment section, numerous channel classification systems exist to characterize stream reaches. Classification systems are useful descriptors of stream behavior and can be applied for extrapolation and prediction. Thus, classification systems that are based on natural physical processes provide the greatest potential for accurate predictions. The simplest forms of channel classification rely on stream order (Strahler 1952) or plan form channel patterns such as sinuosity and braiding intensity (Brice 1960).

Several reviews of fluvial classification systems exist to help evaluate various approaches (Goodwin 1999; Thorne 1997; Downs 1995; Naiman et al. 1992). A brief list and description of reach-scale stream classification systems follows:

- Leopold and Wolman (1957): A simple three-part division of river patterns into braided, meandering, and straight.
- Kellerhals et al. (1976): A more complex system based on a combination of channel pattern, islands, channel bars, and major bedforms.
- Rosgen (1994): A hierarchical system with eight primary stream types based on dimensional properties of the channel.
- Woolfe and Balzary (1996): A process-oriented approach with eight categories that relate rates of aggradation/degradation for the channel and floodplain.
- Whiting and Bradley (1993): A process-oriented system, primarily applicable to headwater areas, with 42 stream classes based on dimensional measures of channel form.
- Montgomery and Buffington (1997): A probabilistic system with seven channel types based on dimensional and qualitative morphologic characteristics.
- Nanson and Croke (1992): A probabilistic classification of 15 floodplain types based on both process and form dimensions.
- Miall (1996): An example-based approach with three major classes divided into 16 fluvial styles that are derived from predominantly qualitative morphologic characteristics.

Sediment Budgets

A complete sediment budget considers the sources, storage, and transport of sediment from a watershed. As described in the Erosion module, evaluation of sediment sources to streams is often sufficient to evaluate the effects of land management activities. However, where it is important to understand the fate of sediment once it enters the stream channel, the storage and transport of sediment will need to be investigated.

The transport, deposition, and storage of sediment can be very complex, with impacts at sites far removed from the original sediment inputs. Prior to conducting a detailed analytical assessment, a qualitative evaluation of channel conditions from aerial photographs and field observations will help to focus the analysis on areas of the stream network that have been most responsive to changes in sediment or flow inputs. Depending on the identified watershed issues, it may also be possible to focus on just coarse or fine sediment yield and transport. Identifying trends in channel conditions and predicting channel response can often be accomplished by a combination of qualitative observations and quantitative analysis with an order of magnitude accuracy.

Erosion
Hydrology

Close interaction among the Channel, Erosion and Hydrology analysts will typically be required to develop a useful sediment budget. The Erosion module can provide qualitative information on geology/soil influences and quantitative estimates of sediment inputs. The Hydrology module can provide data on flood history and the factors that are influencing runoff and stream discharge. Collectively, this information will provide a good, semi-quantitative, systematic understanding of channel processes and sediment distribution patterns.

Sediment budgets are particularly useful for assessing water quality and morphologic channel changes due to altered inputs of sediment or water to streams (Reid and Dunne 1996). The evaluation of changes typically requires characterizing a channel under undisturbed conditions and predicting how those characteristics will change with alterations in sediment or water inputs. Table 3 provides examples of channel issues that can be evaluated with sediment budget techniques. Aerial photos, field surveys, substrate analysis techniques, and flow equations have been addressed in previous sections of this module. Sediment mobility analysis and sediment transport equations are discussed in the following sections.

Table 3. Examples of channel issues and selected techniques for evaluating changes in channel conditions (adapted from Reid and Dunne 1996).

Example Questions	Aerial Photos	Field Surveys	Flow Equations	Substrate Analysis	Transport Equations
How much introduced sediment will be transported out of the watershed?	▼	▼	▼	▼	▼
What proportion of introduced sediment be deposited and where will it be deposited?	▼	▼	▼	▼	▼
How will changes in sediment inputs affect channel form?		▼		▼	▼
How long will it take for the channel to recover from sediment inputs?			▼		▼
How will altered sediment inputs affect water quality?				▼	▼
Will a change in flow cause incision or aggradation?			▼	▼	▼
Where are incision or aggradation likely to occur?	▼	▼		▼	
How fast will a reservoir lose storage capacity?			▼	▼	▼

Sediment mobility analysis

Sediment transport is generally divided into two components: suspended load and bedload. The suspended load (or washload) is composed of sediment that is fine enough to be flushed downstream as part of the water column and that does not accumulate in significant quantities except where overbank flows deposit material on the floodplain. The bedload consists of the coarser sediment fraction that at least intermittently settles to the bed during its downstream migration. While a portion of the bedload is suspended at higher discharges, the distinction between bedload and washload is still appropriate for most situations during the dominant transporting flows.

Bed mobility analysis

The focus of most bed mobility analyses is on which grain sizes can be moved at which discharges. The traditional method for predicting the initial motion of a bed particle involves analyzing the effect of the shear stress from flow near the bed on the lift and drag forces that move a particle out from neighboring grains (Reid and Dunne 1996). This method, often referred to as Shields' function, yields the following equation for rough beds with turbulent flow:

$$\tau_C = \rho gds = 0.06(\rho - \rho_S)gD$$

> Where: τ_C = critical shear stress; ρ and ρ_S = the density of water and sediment, respectively; g = gravitational acceleration; d = flow depth; s = water slope; and D = the diameter of the particle of interest and its neighbors.

Graf (1971) and Richards (1990) provide a good review of the relationship between particle size and channel geometry, the combination of lift and drag forces, and the initiation of particle transport. Reid and Dunne (1996) provide a good summary of empirically derived equations from the scientific literature on initiation of motion for bed particles. Application of particle entrainment equations requires a strong background in fluvial geomorphology and understanding of the scientific literature.

Local field observations, however, can provide a general estimate of particle sizes that are transported during floods and can be a useful check of critical shear stress equations (Reid and Dunne 1996). Maximum mobile grain size can be estimated by measuring the largest particles that were obviously rearranged on gravel bars or that were deposited over new organic debris. Painted rocks and scour chains can also be used as part of a monitoring program to gather data on bed scour before and after floods.

Suspended load grain size estimates

Determining which particle sizes are suspended at various flows is often the first step in evaluating sediment transport rates. The magnitude of the settling or fall velocity reflects a balance between the downward force due to the particle's weight and opposing forces due to fluid viscosity and inertial effect. Viscous resistance is a dominant force for small particles in the silt-clay range but is less important for larger particles (Richards 1982). The suspendibility of a particle is usually defined as follows:

$$P < w_s / u^*$$

Where: w_s is the settling or fall velocity of the particle, and u^* is the shear velocity of the flow.

The settling velocity and shear velocity can be defined as follows:

$$w_s = 9000\ D^2 \quad \text{for silts and clays}$$

$$w_s = [0.67\ Dg\ (\rho-\rho_s)/r]^2 \quad \text{for sands and gravels}$$

$$u^* = (\tau/\rho)^{0.5}$$

Dietrich (1982) describes a method for estimating the settling velocity of natural particles. In the absence of good field data, Komar (1980) provides estimates for suspendibility based on a review of available data. Most of the data, however, were obtained from flume experiments or low-gradient, sand-bedded channels and may not be appropriate for some streams.

Sediment transport

Information on sediment transport rates can be useful for evaluating changes in land management or flow regimes and for identifying locations of potential aggradation or degradation. Suspended sediment transport can also be an important factor for evaluating pollutants because many contaminants move through the stream network attached to sediment rather than through solution (Horowitz 1991).

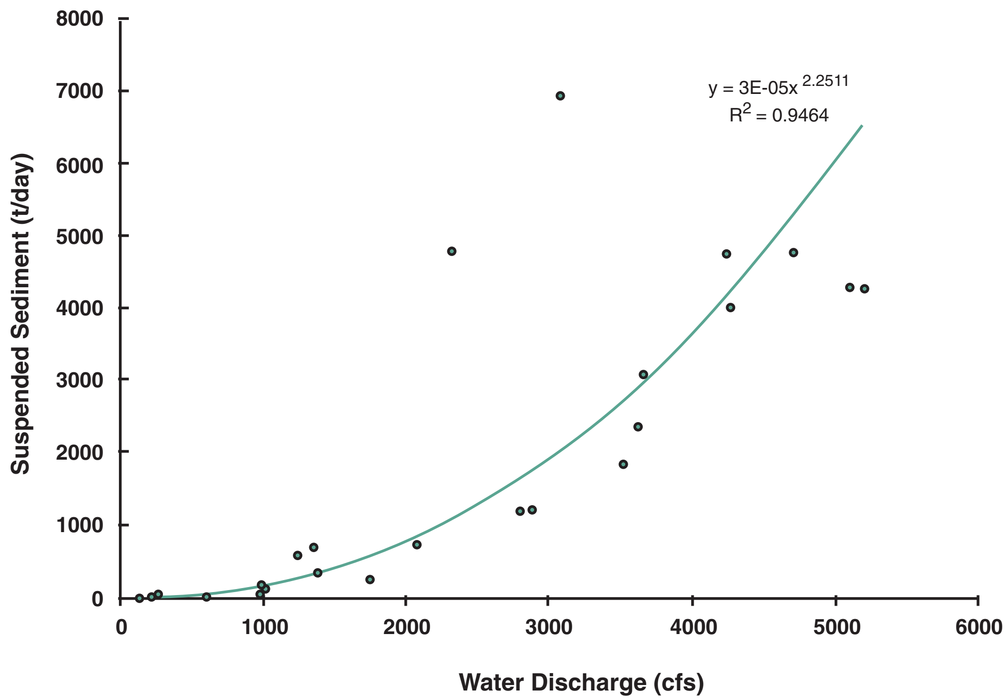
Water Quality

Sediment transport rates can be characterized using any combination of field observations, monitoring data, and predictive equations. The following sections describe methods for determining sediment transport rates for both suspended load and bedload.

Suspended load

The suspended load often represents the majority of sediment transport but is difficult to predict because the transport rate depends more on sediment supply than on channel hydraulics (Reid and Dunne 1996). The primary method for evaluating suspended sediment transport rates requires data from a sediment sampling program. Suspended sediment concentrations can then be related to the stream discharge to provide an estimate of transport rates (Figure 9). Since most sediment transport occurs during floods, it is essential to have sampling data from periods of high discharge. The USGS publishes a great deal of suspended sediment and streamflow data, much of which is available at **http://webserver.cr.usgs.gov/sediment**.

Figure 9. The relationship between suspended sediment and discharge data, Newaukum River, Washington, 1964-1965



Long-term suspended load transport rates can also be estimated by comparing the grain size distribution of sediment inputs with the channel bed composition (Reid and Dunne 1996). The size fraction that is missing from the bed is considered the suspended load. Multiplying the sediment input rate by the proportion of the missing size fraction would then provide an estimate of the suspended load.

Bedload

While no definitive bedload transport equation exists, a number of different transport equations have been developed for sand- and gravel-bedded streams. Data requirements vary among equations, but most require information on channel gradient, depth, width, and sediment character. Graf (1971), Vanoni (1975), and Reid and Dunne (1996) review a number of sediment transport equations and provide further references for detailed application.

Most of the bedload transport equations have a strong empirical basis and are best suited for conditions similar to those used in the development of the equation. Moreover, most equations were developed from flume experiments and depend on a number of assumptions that may limit their extrapolation to natural stream environments. It may be useful to use a number of different equations to assess the accuracy of the estimates. A great deal of judgement and experience are necessary to use these types of equations and to make meaningful interpretations. Some field measurements may be necessary to verify calculated results.

Sediment storage

Sediment is stored in and released from channels and valley floors over time periods ranging from days to centuries. The accumulation of sediment may have important ecological implications and be a significant part of the sediment budget. Dietrich et al. (1982) provide an overview of sediment storage and estimate residence times for several types of storage reservoirs, including debris fans, active channel sediment, and floodplain sediment. Qualitative observations and analysis are often sufficient to assess the influence of sediment storage on the sediment budget. For example, observations or mapping of depositional forms and textures (e.g., gravel bars, floodplains) may be adequate to determine the locations and size fractions of sediment deposition in the watershed or whether sediment volume is increasing or decreasing.

Trends in aggradation and incision can be estimated from a number of field indicators, including changes in the riparian community, cross-sectional surveys at stream gage and bridge locations, or buried structures such as riparian trees, bridge piers, or fence posts. Studies that have evaluated sediment storage include the following:

- Trimble (1983) evaluates long-term alluvial storage in a Wisconsin basin.
- Kelsey et al. (1987) evaluate sediment reservoirs from a basin in northern California.
- Likens and Bilby (1982) address in-channel sediment and nutrient storage behind logs in New England streams.
- Laird and Harvey (1986) examine the effects of wildfire on aggradation and incision in Arizona streams.
- McGuiness et al. (1971) and Matherne and Prestegaard (1988) evaluate seasonal patterns in sediment storage for basins in Ohio and Pennsylvania, respectively.
- Collins and Dunne (1990) plot low-flow water elevations over time and use channel cross-section surveys at bridges to show changes in bed elevation from gravel mining.

Sediment detained by lakes or reservoirs also provides an opportunity to estimate sediment transport and storage. Griffen (1979) reviews methods for determining trap efficiencies in large reservoirs. Heinemann (1981), Moglen and McCuen (1988), and Dendy and Champion (1978) provide methods and data for evaluating the trap efficiency of small reservoirs and detention basins.

References

Arcement, G. J., Jr., and V. R. Schneider. 1989. Guide for selecting Manning's roughness coefficients for natural channels and flood plains. U.S. Geological Survey, Water-Supply Paper 2339, Washington, D.C.

Aldridge, B. N., and J. M. Garrett. 1973. Roughness coefficients for stream channels in Arizona. U.S. Geological Survey Report, in cooperation with Arizona Highway Department.

Barnes, H. H., Jr. 1967. Roughness characteristics of natural channels. U.S. Geological Survey, Water-Supply Paper 1849, Washington, D.C.

Benson, M. A., and T. Dalrymple. 1967. General field and office procedures for indirect discharge measurements. Techniques of Water-Resources Investigations of the U.S. Geological Survey. Book 3, Chapter A1. pp. 1-30. U.S. Geological Survey, Washington, D.C.

Brice, J. C. 1960. Index for description of braiding. Bulletin of the Geological Society of America 71:1833.

Chow, V. T. 1959. Open-channel hydraulics. McGraw Hill, New York, New York.

Collins, B. D., and T. Dunne. 1990. Assessing the effects of gravel harvesting on sediment transport and channel morphology: A guide for planners. State of California Division of Mines and Geology, Sacramento, California.

Corbett, D. M. 1962. Stream-gaging procedure. U.S. Geological Survey, Water-Supply Paper 888, Washington, DC.

Cowan, W. L. 1956. Estimating hydraulic roughness coefficients. Agricultural Engineering 37:473-475.

Dendy, F. E., and W. A. Champion. 1978. Sediment deposition in U.S. reservoirs. Summary of data reported through 1975. U.S. Department of Agriculture, Miscellaneous Publication 1362, Washington, D.C.

Dietrich, W. E. 1982. Settling velocity of natural particles. Water Resources Research 18:1615-1626.

Dietrich, W. E., T. Dunne, N. F. Humphrey, and L. M. Reid. 1982. Construction of sediment budgets for drainage basins. Pp 5-23 in: F. J. Swanson, et al. (eds.). Sediment budgets and routing in forested drainage basins. U.S. Department of Agriculture Forest Service, General Technical Report PNW-141, Portland, Oregon.

Downs, P. W. 1995. River channel classification for channel management purposes. , Pp. 347-365 in: A. Gurnell and G. Petts (eds.). Changing river channels. John Wiley and Sons, Chichester, England.

Dunne, T., and L. B. Leopold. 1977. Water in environmental planning. W.H. Freeman and Company, New York, New York.

Goodwin, C. N. 1999. Fluvial classification: Neanderthal necessity or needless normalcy? Wildland Hydrology, American Water Resources Association, June/July:229-236.

Graf, W. H. 1971. Hydraulics of sediment transport. McGraw-Hill, New York, New York.

Graf, W. L., and K. Randall. 1997. The physical integrity of Arizona streams: A guidance document for river management. Draft report prepared for Arizona Department of Environmental Quality, Contract 95-0137.

Grant, G. 1988. The RAPID technique: a new method for evaluating downstream effects of forest practices on riparian zones. U.S. Department of Agriculture Forest Service, General Technical Report PNW-GTR-220, Portland, Oregon.

Grant, G. E., J. E Duval, G. J. Koerper, and J. L. Fogg. 1992. XSPRO: A channel cross-section analyzer. U.S. Department of Interior, Technical Note 387, Denver, Colorado.

Gregory, K. J., and D. E. Walling. 1973. Drainage basin form and process. Wiley, New York, New York.

Griffen, D. M., Jr. 1979. Reservoir trap efficiency: The state of the art. Journal of Civil Engineering Design 1(4):355-377.

Harrelson, C. C., C. L. Rawlins, and J. P. Ptoyondy. 1994. Stream channel reference sites: An illustrated guide to field technique. U.S. Department of Agriculture Forest Service, General Technical Report RM-245, Fort Collins, Colorado.

Heinemann, H. G. 1981. A new sediment trap efficiency curve for small reservoirs. Water Resources Bulletin 17(5).

Herschy, R. W. 1985. Streamflow measurement. Elsevier Applied Science, London.

Horowitz, A. J. 1991. A primer on sediment-trace element chemistry. Lewis Publishers, Chelsa, Michigan.

Kellerhals, R., M. Church, and D. I. Bray. 1976. Classification and analysis of river processes. Journal of Hydraulics Division 102:813-829.

Kelsey, H. M., R. Lamberson, and M. A. Madej. 1987. Stochastic model for the long-term transport rate of stored sediment in a river channel. Water Resources Research 23(9):1738-1750.

Komar, P. D. 1980. Models of sediment transport in channelized water flows with ramifications to the erosion of the Martian outflow channels. Icarus 42:317-329.

Laird, J. R., and M. D. Harvey. 1986. Complex-response of a chaparral drainage basin to fire. Pp. 165-183 in: R. F. Hadley (ed.). Drainage basin sediment delivery. International Association of Hydrological Sciences, Publication 159, Wallingford, United Kingdom.

Leopold, L. B. 1994. A view of the river. Harvard University Press, Cambridge, Massachusetts.

Leopold, L. B., and M. G. Wolman. 1957. River channel patterns: Braided, meandering and straight. U.S. Geological Survey, Professional Paper 282-B, Washington, D.C.

Leopold, L. B., M. G. Wolman, and J. P. Miller. 1964. Fluvial processes in geomorphology. W.H. Freeman, San Francisco, California.

Likens, G. E., and R. E. Bilby. 1982. Development, maintenance and role of organic debris dams in New England streams. Pp 122-128 in: F. J. Swanson, et al. (eds.).

Sediment budgets and routing in forested drainage basins, U.S. Department of Agriculture Forest Service, General Technical Report PNW-141, Portland, Oregon.

Limerinos, J. T. 1970. Determination of the Manning coefficient from measured bed roughness in natural channels. U.S. Geological Survey, Water-Supply Paper 1898-B, Washington, D.C.

Matherne, A. M., and K. L. Prestegaard. 1988. Hydrologic characteristics as a determinant of sediment delivery in watersheds. Pp. 89-96 in: M. P. Bordas (ed.). Sediment budgets. International Association of Hydrological Sciences, Publication 174.

McGuiness, J. L., L. L. Harrold, and W. M. Edwards. 1971. Relation of rainfall energy and streamflow to sediment yield from small and large watersheds. Journal of Soil and Water Conservation 26:233-235.

Miall, A. D. 1996. The geology of fluvial deposits: Sedimentary facies, basin analysis and petroleum geology. Springer-Verlag, Berlin.

Moglen, G. E., and R. H. McCuen. 1988. Effects of detention basins on in-stream sediment movement. Journal of Hydrology 104:129-140.

Montgomery, D. R., and J. M. Buffington. 1993. Channel classification, prediction of channel response and assessment of channel condition. Washington State Department of Natural Resources, TFW-SH10-93-002, Olympia, Washington.

Montgomery, D. R., and J. M. Buffington. 1997. Channel-reach morphology in mountain drainage basins. Geological Society of America Bulletin 109:596-611.

Myers, W. L., and R. L. Shelton. 1980. Survey methods for ecosystem management. John Wiley & Sons, New York, New York.

Naiman, R. J., D. G. Lonzarich, T. J. Beechie, and S. C. Ralph. 1992. General principles of classification and the assessment of conservation potential in rivers. Pp. 93-123 in: P. J. Boon, P. Carlow, and G. E. Petts (eds.). River conservation and management. John Wiley and Sons, Chichester, England.

Nanson, G. C., and J. C. Croke. 1992. A genetic classification of floodplains. Geomorphology 4:459-486.

Pleus, A. E., and D. Schuett-Hames. 1998. TFW Monitoring Program method manual for the reference point survey. Prepared for the Washington State Department of Natural Resources under the Timber, Fish, and Wildlife Agreement, TFW-AM9-98-002, DNR #104, Olympia, Washington.

Potyandy, J. P., and T. Hardy. 1994. Use of pebble counts to evaluate fine sediment increase in stream channels. Water Resources Bulletin 30:509-520.

Reid, L. M., and T. Dunne. 1996. Rapid evaluation of sediment budgets. Catena Verlag, Reiskirchen, Germany.

Richards, K. 1982. Rivers: Form and process in alluvial channels. Methuen, London.

Richards, K. 1990. Fluvial geomorphology: initial motion of bed material in gravel-bed rivers. Progress in Physical Geography 14(3):395-415.

Rosgen, D. L. 1994. A classification of natural rivers. Catena 22:169-199.

Schumm, S. A. 1977. The fluvial system. Wiley Interscience, New York, New York.

Strahler, A. N. 1952. Dynamic basis of geomorphology. Geological Society of America Bulletin 63:923-938.

Thorne, C. R. 1997. Channel types and morphological classification. Pp. 175-222 in: A. Gurnell and G. Petts (eds.). Changing river channels. John Wiley and Sons, Chichester, England.

Trimble, S. W. 1983. A sediment budget for Coon Creek basin in the Driftless Area, Wisconsin, 1853 to 1977. American Journal of Science 283:454-474.

U.S. Geological Survey (USGS). 1989. Water Resources Data - California, Water Year 1988, Vol. 4. U.S. Geological Survey, Water-Data Report CA-88-4.

Vanoni, V. A. 1975. Sedimentation engineering. American Society of Civil Engineers, New York, New York.

Washington Forest Practices Board (WFPB). 1997. Standard methodology for conducting watershed analysis, version 4.0. Timber/Fish/Wildlife Agreement and WFPB, Olympia, Washington.

Whiting, P. J., and J. B. Bradley. 1993. A process-based classification system for headwater streams. Earth Surface Processes and Landforms 18:603-612.

Wolman, M. G. 1954. A method of sampling coarse river-bed material. Transactions of the American Geophysical Union 35:951-956.

Woolfe, K. J., and J. R. Balzary. 1996. Fields in the spectrum of channel style. Sedimentology 43:797-805.

Form C1. Historical channel changes

Channel segment(s)	Historical changes	Other observations

Form C2. Geomorphic channel type characteristics

Channel type	Description	Channel segments	Potential responsiveness rating			Evidence supporting rating
			Sediment	Runoff	Vegetation	